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FOCUS ARTICLE

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Mitigating floods and attenuating surface runoff with temporary storage areas in headwaters

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Abstract

Temporary storage areas (TSAs) represent a category of soft-engineered nature-based solutions that can provide dispersed, small-scale storage throughout a catchment. TSAs store and attenuate surface runoff, providing new additional storage during flood events. The need for such additional catchment storage will become more urgent as the frequency and magnitude of extreme hydrological events increases due to climate change. Implementation of TSAs in headwater catchments is slowly gaining momentum, but practitioners still require further evidence on how such measures function during flood events. This review focuses on the role of relatively small-scale (<10,000 m^3) TSAs in headwater catchments for flood risk management. It also explores the potential wider benefits for implementing these as part of an integrated catchment management approach. TSA flood mitigation effectiveness is primarily determined by the TSA's available storage prior to the event. At the local scale, this can be represented by the relationship between TSA inputs, outputs and total storage. Factors influencing the local functioning and effectiveness of TSAs are discussed, with potential considerations for optimizing future TSA design and management. Hydrological models have suggested that TSAs could be used to effectively attenuate high magnitude events. However, future considerations should involve addressing the lack of empirical evidence showing TSA catchment scale effectiveness and how local TSA functioning might change in time. Small-scale headwater TSAs offer a holistic and sustainable approach to catchment management that can deliver both local benefits to landowners and wider flood risk mitigation for society.

This article is categorized under:

- Engineering Water > Sustainable Engineering of Water
- Science of Water > Water Extremes
- Science of Water > Hydrological Processes

KEYWORDS

catchment management, flooding, nature-based solutions, runoff, temporary storage areas

1 | INTRODUCTION

Owing to an increasing flood risk globally (Gudmundsson et al., 2021; Hannaford et al., 2021; Kundzewicz et al., 2014), there is a need to create additional storage within catchments, alongside our traditional engineered approaches. For example, Bokhove et al. (2020) estimated that preventing the Boxing Day 2015 floods (<0.5% annual exceedance probability [AEP]) in Leeds (UK) would have required an additional ∼9 million m^3 of storage. Nature-based solutions (NBS) (Nesshöver et al., 2017) are widely promoted as a sustainable and soft-engineered catchment-based mechanism that contribute to providing such storage for managing flood risk (Dadson et al., 2017; Lane, 2017). Example categories of NBS approaches for flood risk management include; woodland creation, soil and runoff pathway management and, river channel and floodplain management (Ngai et al., 2017). However, some measures such as woodland creation need time to establish (Murphy et al., 2020; Stratford et al., 2017) and saturated upland wetlands can often have limited storage capacity during flood peaks, resulting in limited effectiveness during large flood events (Acreman & Holden, 2013; Hare et al., 2022).

Temporary storage areas (TSAs) represent a category of NBS that create "new" additional catchment-based storage via barriers to flow in the landscape or drainage network. They are typically effective the moment they are created. TSAs store and attenuate runoff to reduce flooding and erosion during flood events, while slowing down and disconnecting quick flow pathways. They also have potential wider benefits, such as groundwater recharge (Fennell et al., 2022; Standen et al., 2020). Offline ponds (bunds on floodplains) are one example of a TSA type that increases the natural storage needed to manage extreme events at larger scales (Wilkinson et al., 2019). A number of reviews have highlighted the overall potential of NBS for managing floods (Hewett et al., 2020; Lane, 2017; Suttles et al., 2021) and also some specific NBS measures, such as woodlands (Cooper et al., 2021) and wetlands (Acreman & Holden, 2013). However, none have so far provided a focused review on TSA approaches to improve understanding of their functioning and how they can best provide new additional storage in catchments.

Much is known about the role of larger traditionally engineered TSAs (e.g., washlands and large flood storage reservoirs) for flood management (Boulange et al., 2021; Morris et al., 2005). Small headwater TSAs may offer a cost-effective solution and most importantly, can target areas that would otherwise fall outside the scope of large infrastructure projects (Nesshöver et al., 2017; Waylen et al., 2018). Consequently, this review focusses on small soft-engineered TSAs (<10,000 m^3 storage) in headwater catchments, specifically their potential for flood risk management and wider benefits, while considering this in the context of a changing climate. Headwaters contribute proportionally more to the generation of floods, therefore by targeting surface runoff at the source there is significant potential to reduce flood risk for downstream communities, while also tackling local issues such as erosion. Small TSAs can be successfully integrated within agricultural land and typically require limited land take as the time of inundation is low (1–2 days). They can either be an active part of a managed field under cropping, or an intervention at the field boundary to decrease environmental pressures off site.

Many examples from around the world exist where TSAs have been incorporated in catchments to effectively reduce soil erosion, land degradation and flood risk (e.g., Mekonnen et al., 2015; Nicholson et al., 2019; Tarolli et al., 2014), while also improving water availability, ecosystem services and sustainable agricultural practices (e.g., Aeschbach-Hertig & Gleeson, 2012; Garg et al., 2022; Wingfield et al., 2019). For example, in the steep agricultural landscapes of the Loess Plateau (China), approximately 58,000 leaky barriers have been built for sustainable agriculture and soil and water conservation (Wang et al., 2018). In the UK, the combination of revegetation and leaky barriers in peat moorlands has been shown to delay and reduce peak flows through an increase in surface roughness and new additional storage (Goudarzi et al., 2021; Shuttleworth et al., 2019). In Ethiopia, bunds have been implemented to harvest rainwater and recapture lost sediments along hillslopes, with a terraced structure forming over time (Atnafe et al., 2015; Mekonnen et al., 2015). An international review by Lucas-borja et al. (2021) highlighted that bunds and leaky barriers can increase water storage, sediment retention and vegetation regeneration, which can improve degraded landscapes and mitigate both dry and wet extremes. In Fairfax County (USA), TSAs have been used to prevent nutrient losses, trapping an estimated 2.7 tonnes of phosphorous load annually (Ibrahim & Amir-faryar, 2018). These various case examples highlight the wide range of ecosystem services TSAs can provide. However, the flood mitigation potential provided by small headwater TSAs, in addition to larger engineered TSAs, still needs to be fully realized (Ngai et al., 2017; Wilkinson et al., 2019). While examples exist, the uptake of such measures for flood risk management globally is limited. One main limiting factor for uptake is the diffuse or incomplete evidence on their effectiveness. There is a need to collate the currently dispersed evidence base on TSA effectiveness to support further implementation across catchments globally. Here we review the existing evidence base focusing on how TSAs function locally and at larger catchment scales.

2 | TYPES OF TEMPORARY STORAGE AREAS

TSAs can come in many shapes, volumetric sizes and locations. This review focusses on small soft-engineered TSAs that mimic natural processes and that are integrated within existing headwater practices to mitigate flooding (Figure 1 and Table 1). The regulated volume thresholds for traditional "gray" engineered reservoirs, ranges between >10,000 m^3 (e.g., Wales, Norway) to >100,000 m^3 storage (e.g., Germany, Spain) (ICOLD European Club, 2014) and is influenced by the associated risk of failure. We limit the definition of soft-engineered TSA volumes to <10,000 m^3 to comply with international reservoir legislation. The 10,000 m^3 threshold also ensures that the TSA could fully drain shortly after a high flow event (e.g., within 1–2 days), thus minimizing inundation time and optimizing storage for subsequent events. For example, if the TSA is on valuable arable land, then the risk of crop damage is reduced, and the land can be utilized throughout the year. Specific TSA design is informed by the landscape, climate and potential flood risk, but implementation is still often the result of local factors and individual decisions. This also relates to their primary purpose since TSAs have been used internationally to address many environmental challenges in addition to flood risk (Table 1). However, TSA functioning and principles remain consistent across all contexts by creating new additional water storage in the catchment and reducing connectivity of quick flow pathways.

3 | HOW TEMPORARY STORAGE AREAS WORK

The primary aim of TSAs for flood risk management is to store and attenuate water during storm rainfall events, thereby reducing river peak flows. They are designed to drain quickly after the storm so the available storage and attenuation potential is maximized for subsequent events (e.g., multiday events) (Dadson et al., 2017), otherwise capacity may be reached too early and TSAs will overflow (Metcalfe et al., 2018). The flood attenuation effect has been shown to diminish when TSAs are full, with only a small reduction in velocity due to drag and longer flow pathways (Quinn et al., 2013; Wilkinson et al., 2010). TSAs can also have other hydrological properties such as reducing flow velocities and disconnecting overland flow pathways (Table 1). The effectiveness of the TSA design can be aided by modeling the impact on flows before construction (e.g., Hankin et al., 2017), but this requires time and resources (e.g., historical

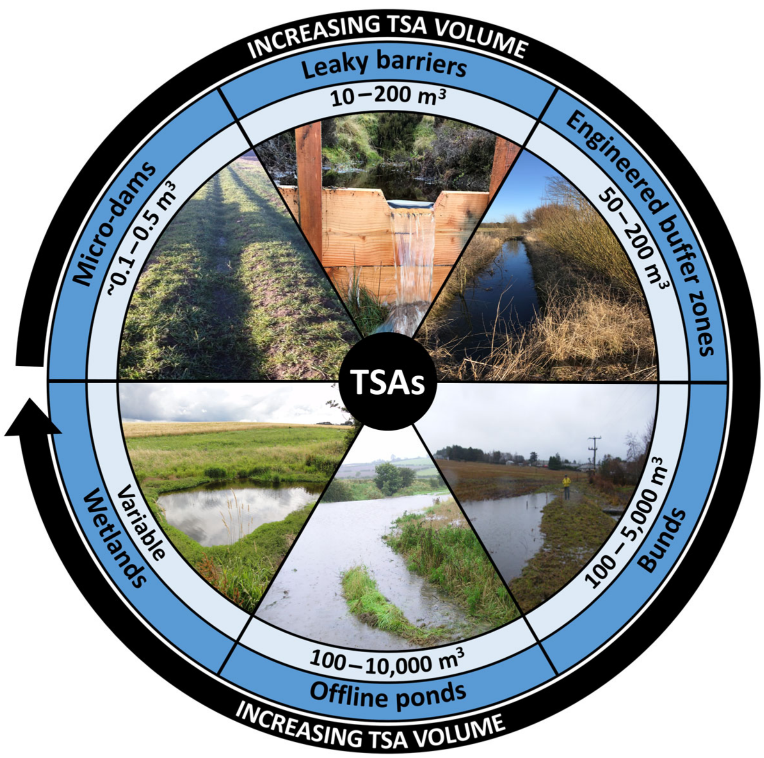

FIGURE 1 Types of small-scale headwater temporary storage areas (TSAs).

TABLE 1 Summary of small-scale headwater temporary storage areas (TSAs).

TSA type	Other similar international terminology	TSA volume (m^3)	Main hydrological functions	Supporting literature
Micro-dams	Micro-dams are a soil and land management practice where small basins/dams are created to attenuate surface runoff, increase water infiltration and capture eroded sediments. Magic margins—*UK* Tied ridges—*UK, Ethiopia, Kenya* Micro basins—*China, Ethiopia* Planting pits | Zai pits—*Kenya, D.R. Congo, Tanzania*	~0.01–0.05	• Storage • Attenuation • Disconnect surface runoff	Stutter & Wilkinson, 2022[WQ,SE,B]; Stutter et al., 2020[WQ,F,SE]; RSPB, 2017[SE,B]; Araya & Stroosnijder, 2010[D,SE]; Biazin & Stroosnijder, 2012[D,SE]; Bagula et al., 2022[D,SE]; Sittig et al., 2022[F,SE]; Sui et al., 2016[F,D,SE]
Engineered buffer zones	Integrated buffer zones—*Denmark, Sweden* Engineered buffer strips—*UK*	50–200	• Storage • Attenuation • Disconnect surface and subsurface runoff	Zak et al., 2019[WQ]; Carstensen et al., 2021[WQ]; Stutter et al., 2020[WQ,F,SE]
Bunds	Ponds—*UK, USA* Detainment bunds—*New Zealand* Check dams—*China, USA, Spain, Saudi Arabia, Jordan, Mexico, Morocco, Tunisia, Iran, Oman, Belgium* Retention polders | Infiltration pits—*Slovakia* Raised buffer: field runoff—*UK, Ireland*	100–5000	• Storage • Attenuation • Disconnect surface runoff	Wilkinson et al., 2010[F]; Nicholson et al., 2012[F]; Levine et al., 2021[WQ]; Ibrahim & Amir-faryar, 2018[F,WQ,SE]; Mekonnen et al., 2015[SE]; Tarolli et al., 2014[SE]; Garg et al., 2022[D]; Standen et al., 2020[WQ,D,SE]; Evrard et al., 2008[F,SE]; Lucas-borja et al., 2021[SE,WQ,F,D]; Barber & Quinn, 2012[WQ,SE]; Wilkinson et al., 2014[F,WQ,SE]
Leaky barriers	Check dams—*China, Spain, Italy, Japan, USA, France, India, Ethiopia, Iran, Slovenia, Taiwan, Mexico, Austria* Johads—*India* Large woody debris (LWD)—*UK, USA* Leaky dams—*UK, Ireland* Gully blocking—*UK* Beaver dam analogs—*USA, Canada* Engineered log jams—*USA, UK*	10–200	• Storage • Attenuation • Velocity reduction • Channel spill	Ngai et al., 2017[F]; Lucas-borja et al., 2021[SE,WQ,F,D]; Munir & Westbrook, 2020[F]; Addy & Wilkinson, 2016, 2019[F]; Thomas & Nisbet, 2012[F]; Grabowski et al., 2019[F,B]; Wren et al., 2022[F]; Wang et al., 2018[SE]; Nicholson et al., 2012[F]; Wohl et al., 2016[F,B]; Shuttleworth et al., 2019[F,B]
Offline ponds	Offline storage ponds—*UK, Ireland* Offline storage areas—*UK* Raised buffer: Offline storage—*UK, Ireland* Johads—*India*	100–10,000	• Storage • Attenuation	Nicholson et al., 2019[F]; Lockwood et al., 2022[F]; Ghimire et al., 2014[F]; National Trust, 2015[F]; Nicholson, 2015[F]; Thomas, 2017[F]; Moore, 2021[F]; Ngai et al., 2017[F]; Wren et al., 2022[F]; Wilkinson et al., 2014[F,WQ,SE]; Nicholson et al., 2012[F]
Floodplain wetlands		Variable—natural system but with some available storage	• Storage • Attenuation	Acreman & Holden, 2013[F]; Acreman et al., 2003[F]; Potočki et al., 2021[F,B]; Oral et al., 2020[WQ]; Hare et al., 2022[F,D,B]; Zhang et al., 2020[WQ,B]

Abbreviations: DO, drought; F, flooding; SE, soil erosion; WQ, water quality.

data), so in practice TSA implementation often relies on site specific knowledge. The factors affecting TSA functioning and effectiveness both locally and at the catchment scale are summarized below.

3.1 | Local functioning and effectiveness

Local TSA functioning and effectiveness are determined by fill rates (input), drainage rates (output) and available storage capacity (storage) (Figure 2a). Although the dominant TSA inputs and outputs vary between TSA types (Figure 2b) and the wider conditions that influence them, fundamentally they can all be represented by the relationship between storage, inputs and outputs according to Equation (1):

$$S_{\mathrm{TSA\_A}\,(t)} = S_{\mathrm{TSA\_A}(t-1)} - \mathrm{inputs}_{(t)} + \mathrm{outputs}_{(t)} \tag{1}$$

where $S_{\mathrm{TSA\_A}}$ is TSA available storage, inputs is all TSA inputs, outputs is all TSA outputs and t is time. TSA available storage is a function of the maximum TSA storage and the inputs and outputs (Figure 2a).

The fluxes in Equation (1) are predominantly influenced by the rate and volume of surface and subsurface runoff generated in the catchment, which affects all TSA types (Figure 2 and Table 1). These are ultimately controlled by precipitation and antecedent conditions, meaning TSA functioning can vary temporally (Lockwood et al., 2022; Metcalfe et al., 2017; Wilkinson et al., 2010). Climate change is set to intensify the hydrological cycle leading to an increase in precipitation extremes, which will affect surface and subsurface runoff generation (Gudmundsson et al., 2021; Hirabayashi et al., 2008; Pokhrel et al., 2021; Zhang et al., 2019). The frequency of dry days is also expected to increase across most regions (Polade et al., 2014) and increases in extreme wet days will be counteracted by a decrease in light to moderate precipitation days (Thackeray et al., 2018). Collectively, this is set to increase the occurrence of consecutive wet and dry extremes in some regions (Swain et al., 2018), which may considerably increase the magnitude of multiple TSA inputs (Figure 2) and potential exposure to extreme flash floods (Zhang et al., 2019). Meta-analysis of regional

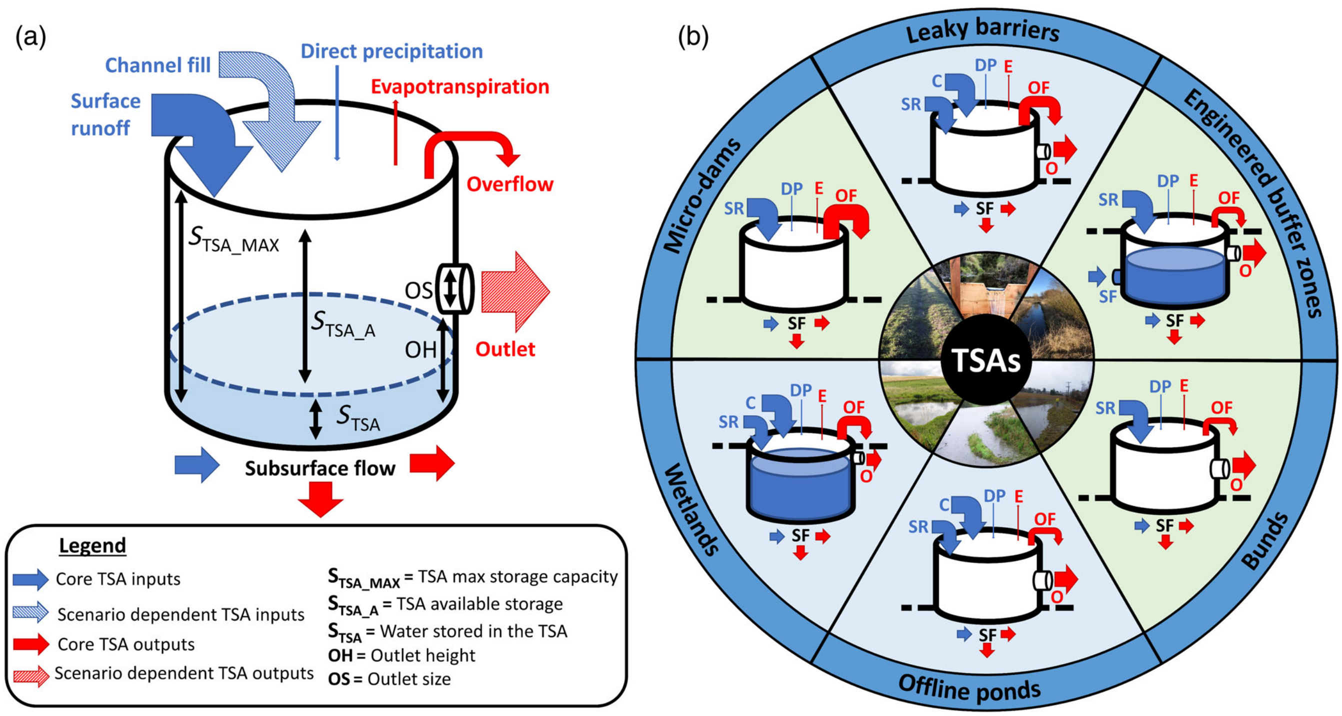

FIGURE 2 Temporary storage area (TSA) conceptual models. (a) TSA conceptual model showing inputs, outputs and factors affecting available storage capacity. Dominant flows are represented by larger arrows. (b) TSA conceptual models for each small-scale headwater TSA. Green segment, main TSA input is surface runoff; Blue segment, main TSA inputs are channel fill and surface runoff; Dashed line, ground level; SR, surface runoff; SF, subsurface flow; C, channel fill; DP, direct precipitation; O, outlet; OF; overflow; E; evapotranspiration.

studies by Merz et al. (2021) found increases in the 100-year flood peak runoff during the 21st century for much of NW Europe, sub-Saharan Africa, eastern and southern Asia, and areas in North and South America, whereas decreases were projected for eastern Europe and northern Africa. Extreme dry conditions can increase soil water repellency (hydrophobicity), which is associated with increased runoff, erosion and flooding (Doerr et al., 2006; Jordán et al., 2013; Smettem et al., 2021). There is a general finding that at large scales, flood risk is affected more by climate change than land use (e.g., Yang et al., 2021). It is clear that due to climate change, more storage is needed within catchments to attenuate increasing runoff rates (Bokhove et al., 2020), which will also impact the magnitude of TSA inputs (Figure 2).

Agricultural land management practices have been shown to significantly impact runoff generation by altering soil structural conditions and vegetation cover (Holman et al., 2003; O'Connell et al., 2007). Heavy machinery and livestock grazing can potentially degrade soil structure, which has been associated with greater flood risk (Alaoui et al., 2018; Pattison & Lane, 2012; Wheater & Evans, 2009). This assumption is often based on plot scale experiments where land management practices (i.e., livestock, tillage and trafficking) increase runoff and compaction (Deasy et al., 2014; Hallett et al., 2016; Jackson et al., 2008; Kim et al., 2010; Seehusen et al., 2019). During critical times of land management operations, wet soils are prone to compaction and structural damage (Arvidsson et al., 2001; Earl, 1997; Holman et al., 2003). Compacted soils in the TSA contributing area can potentially increase the volume of surface runoff input due to impeded infiltration and limited soil water storage capacity (Figure 2) (Alaoui et al., 2018). Soil hydraulic properties are also subject to temporal variations due to both natural factors and tillage (Kargas et al., 2016; Schwen et al., 2011; Strudley et al., 2008). Subsoil compaction may extend to depths of 1 m or more (Spoor et al., 2003), can persist for decades after (Batey, 2009; Etana et al., 2013; Kellner & Hubbart, 2016) and is extremely difficult to alleviate (Jones et al., 2003). The formation of a subsoil plow pan also impedes vertical infiltration and enhances interflows (Bertolino et al., 2010), resulting in greater surface and subsurface runoff inputs (Figure 2). At larger catchments and for extreme events, the effect of land use diminishes and soil saturation plays a greater role in runoff generation (Rogger et al., 2017). However, with an increasing population and higher demand for food production, greater agricultural pressures may be exerted on our landscapes, meaning land use in the future could be a real issue in the global context (Hewett et al., 2020), while locally affecting the need for and functioning of TSAs to address these issues.

The rate and volume of TSA input is also influenced by the design (Figures 1, 2 and Table 1). For example, where TSAs are implemented in sequence, the design and therefore output of upstream TSAs will affect the input of downstream TSAs. Furthermore, channel filled TSAs (Figure 2b) such as offline ponds will predominantly fill with surface runoff until high channel flows are diverted into the feature (Lockwood et al., 2022). The magnitude of channel fill (Figure 2) is therefore determined by the channel inlet-filling thresholds, which should allow for direct channel input while considering enough available storage during high flow events (Nicholson et al., 2019). The principles of offline TSAs are similar to larger flood storage structures such as washlands, where the inlet spill is optimized to manage certain magnitude events (Morris et al., 2005). Lockwood et al. (2022) found that the channel inlet-fill height and outlets are essential criteria for effective TSA functioning across a range of event sizes. Peak flow attenuation was shown to diminish for smaller events, where the dominant input was surface runoff and there was no channel fill. Lockwood et al. (2022) also described a case where the channel inlet-fill height was deemed too high for one offline pond, which resulted in lower attenuation levels (<1.5% peak flow reduction [41% AEP event]).

TSA outputs are primarily controlled by the design when full and the soil properties affecting vertical drainage within the TSA footprint when levels are relatively low (Figure 2). The degree of overflow depends on the height of the TSA structure and/or outlet in relation to the storage capacity (Wilkinson et al., 2010). TSAs with a lower storage capacity (e.g., microdams) will have a greater volume of overflow, whereas larger TSAs (e.g., offline ponds) may require outlets to maintain available storage (Figure 2b and Table 1). Therefore, the total storage of the TSA and the need to drain relatively quickly needs to be considered to determine the appropriate outlet rate (Figure 2). For example, an ~800 m^3 offline pond in Belford (NE England) was built on productive farmland, so it was designed to empty within 24 h (Wilkinson et al., 2010), which was later reduced to 5 to 6 h through modifications (Nicholson et al., 2012). Meanwhile, offline ponds in the Tone and Parrett catchments (SW England) were built on unused field margins and could take up to 7 days to empty following high flow events (Lockwood et al., 2022). Consistently high pond volumes (e.g., >66% as in Lockwood et al. (2022)) could also affect the TSA available storage in future extreme events. To best accommodate temporal variations in volume, TSA design could consider adjustable outlets, so that when full, output is in proportion to input (National Trust, 2015). The TSA design might also involve trade-offs between different ecosystem services. For example, the outlet pipe (diameter and height) could be changed to increase inundation time for TSAs primarily used for soil and water conservation (e.g., Boardman & Foster, 2020). However, available storage for multi-day events may be decreased due to sedimentation or standing water. Overall, to ensure TSA sustainability, designs should ideally be flexible enough that post-construction they manage temporal variations through adjustable inlet heights and outlets, mitigate multiple environmental ills and buffer against future climate extremes.

Soil infiltration within the TSA wetted footprint is a dominant output at lower volumes for all TSA types when the water level is below that of the maximum storage or outlet pipe height (depending on the design) (Figure 2 and Table 1), that is, during the first stages of filling and last of emptying. The rate of water lost via subsurface flow is controlled by soil hydraulic conductivity, antecedent wetness conditions and the height of water per unit area (Figure 2). TSA functioning therefore depends on soil type and soil hydraulic properties, which are both spatially and temporally variable. Soil structure can change over periods as short as major weather events or tillage (Castellini et al., 2019; Schwen et al., 2011) and over longer periods through agricultural and biological activity (Lu et al., 2020). Prolonged periods of inundation have been shown to reduce soil infiltration rates (Hallett et al., 2016; Hao et al., 2011) and when drainage is impeded in wetter soils, greater slumping (Augeard et al., 2008) and surface sealing can occur (Assouline & Mualem, 2001). TSAs are usually positioned at the lowest point of a field, which can increase the risk of compaction due to hillslope hydrology. On the other hand, if present, field drains can help maintain TSA functioning by increasing soil water storage capacity (Marshall et al., 2009). Wetter soils within the TSA footprint are also susceptible to structural degradation (Hamza & Anderson, 2005), which can be exacerbated by livestock trampling or tractor passes, creating an anisotropic soil pore system (Pagliai et al., 2003; Peng & Horn, 2008) that induces mostly horizontal water fluxes (Horn et al., 2003; Pagliai et al., 2003). A bund could be designed to increase TSA storage capacity and provide a pass for machinery. Soil structural degradation within the TSA wetted footprint could reduce drainage via subsurface flow, thus increasing the time of inundation and reducing TSA available storage (Figure 2). Understanding the soils and geology within the catchment is therefore important for optimizing TSA effectiveness (Reaney, 2022; Standen et al., 2020).

Management is critical for TSA longevity and effectiveness, due to temporal variation in soil hydrological and sediment properties. Verstraeten and Poesen (1999) noted that TSAs require periodic maintenance to preserve storage capacity, especially where erosion and sedimentation rates are high. Fine particles are deposited within the TSA footprint as surface runoff is collected. This in turn has been shown to reduce local water infiltration capacities (Lassabatere et al., 2010) and will increase the frequency and duration of inundation (Figure 2). To maintain storage for flood management, upstream sediment traps could be implemented to collect sediment before it enters the TSA. Vegetation could be used within the TSA wetted footprint to improve soil infiltration rates (Figure 2); however, this depends on whether the TSA is located on land under cropping or not. Plant roots have been mostly shown to improve infiltration capacity (Fischer et al., 2015), although plant roots can decrease soil hydraulic conductivity in coarse textured soils (Lu et al., 2020). Greater soil organic content can decrease the risk of soil compaction and erosion (Hamza & Anderson, 2005; Nawaz et al., 2013), which in turn improves the soils ability to store carbon (Amézketa, 1999). In Ethiopia, TSAs are grassed to improve sediment trapping and infiltration, with the grass species and grazing intensity important considerations (Mekonnen et al., 2016).

3.2 | Catchment scale effectiveness

The flood mitigation potential of TSAs at the catchment scale has been demonstrated, but primarily for relatively small catchments (<10 km^2) (Bourke et al., 2022; Ngai et al., 2017) and not extensively. Uptake by practitioners remains limited (Brillinger et al., 2021; Raška et al., 2022; Schanze, 2017), with one factor being evidence gaps surrounding their catchment scale effectiveness (Dadson et al., 2017; Hartmann et al., 2022), particularly their performance during extreme events and in larger catchments (Collentine & Futter, 2018; Wilkinson et al., 2019). It can also be difficult to distinguish effects of specific change within the catchment from multiple dispersed interventions (Hankin et al., 2019; Pattison & Lane, 2012), which is typically compounded by a lack of long-term monitoring (Black et al., 2021).

TSAs primarily aim to reduce and delay peak flows at catchment outlets where flood risk is high. Core metrics of interest are peak flow reduction, change in lag time and change in travel time of peak. Those studies that have investigated TSA catchment scale effectiveness involved both modeling and empirical approaches, with modeling the most common for assessing larger scale impacts. Ideally, modeling studies should be verified by empirical data, however these are much rarer (Wheater et al., 2008). Contrary to the Dadson et al. (2017) review, recent studies have demonstrated that TSA flood peak attenuation improves at higher flows due to additional storage being fully utilized (Black et al., 2021; Hankin et al., 2021; Kay et al., 2019). For example, leaky barriers cause spillage onto the floodplain only at high flows. Exactly how TSAs affect lag time for events of different magnitudes is quite unclear at larger catchment scales, due to the dominant control of other environmental effects on lag time, such as tributary inputs, especially when the proportion of the catchment subject to TSAs is small (Black et al., 2021). In addition, defining peaks can be uncertain, especially for low flow events (Wilkinson et al., 2010) and extracting lag times requires detailed catchment rainfall knowledge.

Peak flow reduction is therefore the most commonly used metric to assess TSA catchment scale effectiveness. Figure 3 demonstrates that generally, percentage peak flow reduction increases with total TSA volume per km^2. The figure collates the available evidence from international offline pond studies and their effect on peak flows across a range of catchment sizes and event magnitudes. Only offline pond studies were selected as the evidence base for this TSA type was one of the most extensive, but also to ensure peak flow reduction was attributed to a TSA rather than disentangling the effect of multiple NBS measures. Importantly, Figure 3 highlights the lack of purely empirical studies and reinforces the need for monitoring the effect of TSAs at the catchment scale. 'Empirical model' studies presented in Figure 3 used local TSA data to simulate the catchment scale effect of the interventions, while model studies explored more broadly the required storage needed to attenuate higher magnitude events (e.g., 1% AEP).

Predominantly, TSA effectiveness is determined by the new additional storage needed in the catchment to attenuate an event (Figure 3). Figure 3 suggests that to achieve >10% peak flow reduction from offline ponds, a total additional storage of at least 2000 m^3/km^2 is required across a range of catchment sizes and event magnitudes. To mitigate high magnitude flood events across all catchment sizes it has been previously estimated that 2000–4000 m^3/km^2 (Nicholson et al., 2019) or up to 10,000 m^3/km^2 (Chappell & Page, 2020) is required. These studies considered storage in the broadest context, and it could also be created through measures other than TSAs, such as floodplain reconnection or traditional hard engineering approaches. Nevertheless, scaling up the effects of TSAs to larger catchment scales does need to consider the potential effects on synchronicity (Pattison et al., 2014), ensuring each intervention is spatially evaluated to avoid the hydrologic response between subcatchments being inadvertently synchronized, thereby increasing instead of reducing flood peaks. However, complexities in rainfall patterns, for example, how a storm moves across a catchment or whether it is localized within one sub-catchment, mean that these synchronization issues could vary storm to storm (Wilkinson & Bathurst, 2018).

There is also debate on how best to distribute additional storage throughout the catchment. Wilkinson et al. (2019) concluded that there was an urgent need to understand whether the cumulative storage of many small TSAs dispersed throughout the landscape could deliver the same or different flood risk management benefits as one large TSA. For a headwater catchment in the UK, Fennell et al. (2022) reported that TSA scale (total storage volume and spread of features) was more important than location (soil type) for high and low flow management, with many small TSAs dispersed throughout the catchment across soil types having the greatest effect on flood peaks.

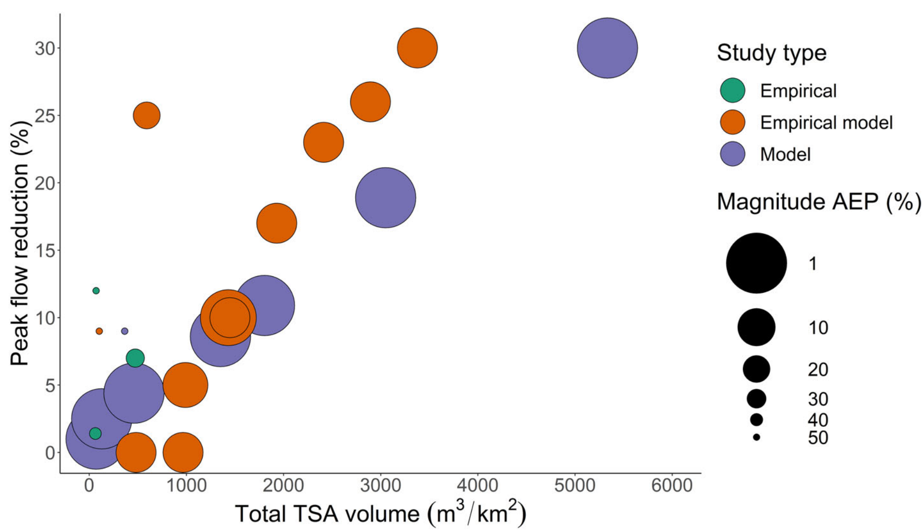

FIGURE 3 The effectiveness of offline pond temporary storage areas (TSAs) for peak flow reduction. Magnitude is measured by annual exceedance probability (AEP) Offline pond studies: Ghimire et al. (2014), Lockwood et al. (2022), Moore (2021), National Trust (2015), Nicholson (2015), Nicholson et al. (2019), and Thomas (2017).

4 | FUTURE CONSIDERATIONS AND CONCLUDING REMARKS

This review has highlighted the potential for small-scale headwater TSAs to contribute to flood mitigation and wider benefits. However, there are challenges in understanding how small-scale headwater TSAs affect larger scale catchment-based processes. Future considerations that need to be addressed to enable a more widespread effective implementation of TSAs are summarized below.

TSAs are multifunctional features that can provide multiple benefits when addressing environmental challenges (Table 1). Where TSAs are located on field boundaries (e.g., buffer strips), they could maximize the potential of this land to deliver multiple environmental benefits (Stutter et al., 2020; Stutter & Wilkinson, 2022). For example, increasing plant species richness within the TSA footprint can improve both soil infiltration by the action of roots, and biodiversity by providing resources for pollinators and other beneficial insects (Sidhu & Joshi, 2016). TSAs can also capture nutrient rich eroded sediments during storms (Boardman & Foster, 2020; Ibrahim & Amir-faryar, 2018; Wilkinson et al., 2014), which can be replowed into the field to reduce nutrient losses (Scholz et al., 2013) and maintain TSA storage capacity (Verstraeten & Poesen, 1999). Sediment removal and early management can improve wetland restoration outcomes by decreasing the abundance of invasive species and increasing habitat interspersion (Larson et al., 2020; Winikoff et al., 2020). However, increasing TSA available storage through sediment removal or lowering wetland water levels may conflict with other wetland priorities, such as maintaining biodiversity (Acreman & Holden, 2013). Therefore, trade-offs and tensions can exist between the TSA primary and additional benefits (Giordano et al., 2020). There is current debate about the realization of these additional benefits (e.g., ecological), which are often missed through conventional approaches such as cost–benefit analysis (Short et al., 2019). Kumar et al. (2021) highlighted that there is no standard approach for measuring NBS and monitoring frameworks to capture their additional benefits are virtually nonexistent.

TSA implementation on private land currently relies on the active engagement of landowners (Holstead et al., 2017; Howgate & Kenyon, 2009; Posthumus et al., 2008), usually considering such approaches as part of an agri-environmental scheme or other funding mechanism, but uptake varies depending on NBS governance, national policies and the economic impacts of land use change (Fantappiè et al., 2020; Raška et al., 2022; Wells et al., 2020). Many countries operate agri-environmental schemes that provide subsidies to land owners to provide viable NBS schemes that have off-site benefits (Bartolini et al., 2021; Cullen et al., 2021; Mills et al., 2021). Headwater TSAs have minimal impact on farm productivity and economics (Hewett et al., 2020), as they remain empty for most of the year and require minimal land take compared to other NBS (e.g., tree planting) or large engineered flood prevention approaches (e.g., reservoirs). Furthermore, engineered buffer zones can provide financial incentives to landowners through biomass production (Rosa et al., 2017; Zak et al., 2019). McCarthy et al. (2018) showed that the benefits often outweigh the costs associated with NBS implementation. These local benefits need to be communicated to landowners and managers, especially those which could be valuable to farming (AQUARIUS Project, 2012).

Internationally, the primary motivation for implementing TSAs may vary, but how they work remains the same. If TSAs are considered multifunctional features and part of a holistic approach to catchment management, multiple objectives can be met, offering a no-regret climate change adaptation strategy (Heltberg et al., 2009) with added benefits that should ensure sustainability. An integrated catchment-based approach and large-scale payment-for-outcome schemes could be used to promote sustainable agriculture, land management and provide environmental benefits to society, such as flood risk management (Arnott et al., 2019; Klaar et al., 2020; Šumrada et al., 2021).

Challenges still remain on how best to compensate private landowners where needed, and how to deliver long-term catchment-based flood risk management. Compensation for flood storage depends on the likelihood of flooding and damage within the retention area (Kis et al., 2022). In Europe, large scale flood alleviation projects have required considerable land take (3–250 km^2) (Glavan et al., 2020; Kis et al., 2022; Natural Water Retention Measures (NWRM), 2013; Ungvári & Kis, 2020). From a policy perspective, the cost of one-off payments to landowners to compensate lost land or flood events from such large-scale projects (Fenn et al., 2015; Kis et al., 2022) could be reduced by small TSAs that should incur less costs and provide additional benefits. However, maintenance costs should be considered and there also needs to be clarity on ownership of TSAs post-installation to avoid issues regarding upkeep and the responsibility of adjustable TSA designs for temporal variations (Bark et al., 2021). Community implementation of NBS through bottom-up approaches has been shown to promote ownership of the features, while improving the communities' resilience to climatic events (Campos et al., 2016; Esteves, 2017).

Another key challenge relates to the expansion of the TSA empirical database, which needs to consider long-term monitoring of features to capture the flood mitigation and potential wider benefits. The lack of empirical evidence for

TSA effectiveness is most pressing for larger catchment scales (>50 km^2) and during large events. Assessing catchment scale effectiveness is still predominantly reliant on modeling studies, which should be informed by empirical data collected at the relevant scale. Modeling could also support the research required to determine how best to distribute new additional storage from TSAs within catchments in different landscapes. This should also consider the role of place (e.g., soil type and catchment setting) when determining the most important factors for catchment scale TSA effectiveness.

Longer term monitoring would also allow for a better understanding of the temporal variations in TSA functioning. Previous TSA studies have often neglected the role of changing soil properties for understanding local TSA functioning and flood mitigation effectiveness. More research is needed to understand how TSAs interact with soils and the impact of time dependent soil structure changes on local TSA functioning, which could explore how soils within the TSA wetted footprint respond to frequent flooding and sedimentation. This highlights a need for long term soil monitoring within the TSA wetted footprint and contributing area to understand changes in soil properties. TSAs could be used to alleviate soil issues such as hydrophobicity through rewetting (Doerr et al., 2000; Horne & McIntosh, 2000; Rakhmatulina & Thompson, 2020) or support crop production in dry regions by recapturing nutrient rich sediments and increasing soil moisture (Bagula et al., 2022; Biazin & Stroosnijder, 2012; Wang et al., 2022). Better knowledge of how all TSA types (Figures 1,2 and Table 1) work across a range of soil, physical and management conditions under various states of wetness will help inform future TSA design and management, ensuring TSAs remain effective in the context of a changing climate.

Extreme hydrological events are already occurring and are only set to increase in magnitude and frequency due to climate change. There is a need to create new additional water storage within multifunctional landscapes to attenuate surface runoff and manage extremes at larger scales. Small headwater TSAs offer a sustainable solution to catchment management and should be integrated within a wider catchment-based approach to managing floods.

AUTHOR CONTRIBUTIONS

Martyn T. Roberts: Conceptualization (equal); formal analysis (lead); investigation (lead); methodology (lead); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Josie Geris:** Conceptualization (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); supervision (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Paul D. Hallett:** Conceptualization (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); supervision (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Mark E. Wilkinson:** Conceptualization (lead); formal analysis (equal); funding acquisition (lead); investigation (equal); methodology (equal); supervision (lead); visualization (equal); writing – original draft (equal); writing – review and editing (equal).

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The authors have declared no conflicting interests.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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